LARGE CALIBER GUN TUBE MATERIALS SYSTEMS DESIGN

J.S. Montgomery[1], and R.L. Ellis[2]

[1] *U.S. ArmyResearch Laboratory, Aberdeen Proving Ground, MD 21005*
[2] *U.S. Naval Surface Warfare Center, Dahlgren, VA 22448*

The requirements of future gun systems have put increasing demands on the materials of construction. Our knowledge of the gun tube service environment and materials now allows us to use a materials systems design approach to design new gun systems.

The gun tube environment and current gun tube materials, properties, dimensions, and fabrication methods will be reviewed, as well as the erosion test methods that have been used to characterize the in-bore environment. Fatigue, erosion and muzzle wear are the three predominant reasons for gun tube retirement, and each of these phenomena will be examined.

The materials systems design approach will be used to examine a number of possible materials systems designs for advanced gun systems, and we will highlight the strengths and weaknesses of these designs.

BACKGROUND

For the purposes of this paper, we will only be considering the gun tube subsystem, not the gun carrier subsystem, the propellant subsystem, or the projectile subsystems. In actual practice, the design of a gun system must take these components into consideration, and, ideally, all should be designed simultaneously. If one examines existing "successful" gun systems, one sees that most had their gun, propellant and projectiles designed at about the same time. It is beyond the scope of this paper to consider gun system components outside the tube subsystem. Furthermore, we will only be considering large caliber gun tubes. These are tubes that are typically greater than 40 mm caliber, and are used in the tank gun (direct fire) and in the artillery (indirect fire) roles. Gun tube designs that use artificial cooling of the gun tube by forced liquid cooling of the jacket or evaporative cooling of the bore will not be considered, but these features may be easily incorporated in the analysis.

Because gun tubes have been around a long time, they have undergone an evolutionary optimization. The wise man pays careful attention to this before attempting a "revolutionary" approach to materials design. An excellent background on gun tube design may be found in the AMC pamphlet [1].

The perspective of this paper will be framed in the language of systems design as applied to materials. For a background on this, the reader is referred to the many papers by G.B. Olson and his students [2-9]. The one-page flow-block diagram for a tank gun is shown in Figure 1. Any materials system can be examined in terms of PROCESSING/ MANUFACTURING, STRUCTURE/COMPOSITION, PROPERTIES/BEHAVIOR and PERFORMANCE/FUNCTIONS. COST is located on one end next to PROCESSING/

MANUFACTURING, because this step is normally associated with the greatest cost. On the other end, near PERFORMANCE/FUNCTIONS is VALUE. This is the value that the system provides to the user. Cost is very important to the gun tube materials system design, because if a gun system becomes too costly compared with the value provided to the user by a competing type of system (such as missiles), the user will vote with his wallet (assuming a free market).

We break the gun tube down radially into three components or zones: the coating, the liner and the jacket. A gun tube may have all three of these components made from the same material (many do), or, at the other extreme, it may have a continuous gradation of materials from the coating through the liner to the jacket. This is known as a functional gradient material, or FGM. There are past and present Army and Navy SBIR programs whose objective is to produce a FGM gun tube.

Currently, all fielded gun systems (that the authors are aware of) use tubes that are monobloc steel, except the .50 cal M2 machine gun, which has a Stellite insert. The steel is generally a low alloy medium carbon Ni-Cr-Mo steel tempered in Stage III. Steel is an excellent material for this application because it possesses the necessary specific strength, is somewhat resistant to erosion, is fabricable, and inexpensive. In service, it behaves predictably and repeatably.

Before WWII, the service life of gun tubes was generally based on fatigue. As performance increased during that war, thermochemical erosion of the bore became the determining factor of service life. This trend has shown no signs of abating. Throughout the gun's life, the amount of erosion is measured with various kinds of mechanical gages. At some point the amount of erosion exceeds a certain limit, based on prior testing, and the tube is retired from service. Ultimately, however, the performance attributes that are degraded by erosion are dispersion and muzzle velocity. Erosion would play no role in gun tube (or propellant) materials design if it did not degrade these valuable performance attributes.

COATINGS

The coating is the most difficult part of gun materials systems design. The list of required and desired properties is long, and a material that satisfies the list completely does not exist. Trade-offs must be made, and that is where systems design comes in. There are also very constraining requirements of the coating process. The process must be able to produce a coating with extremely good adhesion, to the point where it is considered to be metallurgically bonded. In welding terms, it must have 100% joint efficiency. To this end, some interface mixing is desirable. Because large caliber gun tubes will continue to be made from autofrettaged quench-and-tempered low-alloy steel into the foreseeable future, the coating process must not heat the steel substrate to above the stress-relief temperature of about 400°C. There are geometrical and produceability constraints as well. The process must be able to coat the inside of a tube as small as 90 mm and as long as 9 m. If the tube is rifled, it must be able to coat the sides of the rifling. Finally, the process should allow the whole tube to be coated within one 8 hr shift.

It is very difficult to adequately simulate the gun environment for the purposes of coating testing. Furthermore, a particular gun system will have a unique propellant gas chemistry, wall temperatures, heat input to the barrel, ballistic cycle time and duty cycle. A capacitive discharge or excimer laser can simulate the thermal pulse. A vented combustor or ballistic compressor can simulate the thermal pulse, the propellant chemistry and the gas

cross-flow velocity. Pin-on-disc testing can simulate the mechanical forces and rotating band wear in a gun tube, although the higher sliding speeds are difficult to obtain. Adhesion/ cohesion can be checked by scaled-up scratch testing. After a series of these kind of laboratory tests have been conducted, coatings are generally tested in a subscale gun system before the investment is made in large caliber.

Adhesion/Cohesion

The coating must possess complete adhesion when produced and throughout its service life, since coating life determines gun tube life. The coefficient of thermal expansion should be similar to or higher than substrate, so that when the tube heats, there is no stress acting to pull the coating off. The modulus of the coating should be similar to or lower than substrate so that when the tube is stressed by firing, the stress is transferred to the substrate. There should be no chemical reaction with substrate. This is a difficult requirement to meet: the coating is in intimate contact with the substrate, and the couple is heated by firing. Most materials couples will react, or at least, will interdiffuse. It is desirable for the coating to be under a residual compressive stress. Such a stress state will promote adhesion. "Cohesion" is the cohesiveness of the coating layer itself. It does no good to have complete adhesion if the coating separates (delaminates) within the coating layer.

Chemical Barrier

Once a coating can be made to stick, it must provide a chemical barrier for the substrate against the erosive effects of the hot propellant gasses. The coating must be free from cracks as-produced and in service. Any cracks will be exploited by the very aggressive environment of propellant gasses during firing, and the substrate will be attacked. These cracks will also be wedged and racheted open by microscopic debris during firing, and after firing, the substrate can be attacked by simple corrosion. There should be a low solubility of the elements hydrogen, carbon, nitrogen and oxygen if these will degrade the substrate (as in the case of steel). The coating should also have a low reactivity to these elements, that is, there should not be a large negative free energy of reaction at the temperatures, pressures and chemistry encountered during firing. The CO/CO_2 ratio of the propellant gasses is typically used to measure their carburization potential, and for fielded solid propellants is in the range of about one to ten. Liquid propellant LP 1846 has a very different CO/CO_2 ratio, about 0.02. This is very oxidizing, and leads to rapid erosion of the combustion zone materials. When the propellant was modified by adding just 4.76% fuel (TEAN), the CO/CO_2 ratio increased to about 0.4, decreasing the rate of erosion of PH13-8Mo by over 16 times [10].

Thermal Barrier

The coating also serves as a thermal barrier, insulating the substrate from the damaging effects of heat input from high temperature propellant gasses. A good thermal barrier should have a low thermal conductivity and a high heat capacity. Additionally, it should be thermally stable and "heat resistant." This term encompasses a number of properties, including: a high melting point, a high hot hardness, thermal shock resistance, and

a lack of phase transformations throughout the service temperature envelope (typically, -60°F to the melting point). The thermal properties of the coating, along with its thickness, should prevent phase transformation or reaction of the substrate. It does this by damping out the high temperature pulse. In the case of a steel substrate, the martensite $\rightarrow$ austenite phase transformation occurs at about 727°C. When this temperature is exceeded, the transformation causes a discontinuity in the thermal expansion coefficient, resulting in large local strains. Because the steel is also soft at this temperature, the strain is taken up plastically rather than elastically. On rapid cooldown, such as in a gun, the plastically-deformed austenite transforms back to martensite. This martensite, however, is hard and brittle, and so cracks instead of plastically deforming to accomodate thermal stresses on further cooling. This is called heat checking. Obviously, this phase transformation really wreaks havoc with the integrity of the coating. It will tend to thermal fatigue and crack the coating, as well as promote de-adhesion.

Mechanical Properties

The coating/liner must be strong enough at the service temperatures to withstand the forces imposed by the projectile (rotating and obturator bands and bourellet) and the propellant gas "wash." If the tube is rifled, there must be sufficient strength to support the rifling torque. Furthermore, a high velocity rifled gun tube is subject to muzzle wear [11]. The coating/liner should possess enough strength to withstand this kind of mechanical wear. Rotating band wear is accelerated by a rough bore surface. If the band wears out before muzzle exit, there will be projectile steel sliding against the bore, leading to muzzle wear. The coating/liner must be smooth enough to preclude premature band wear-out.

Candidate Coating Materials and Processes

A coating material that possesses all these properties does not exist at present. If one looks at the periodic table of the elements and their phase diagrams, one can generate a fairly short list of candidate materials in two classes: (1) refractory metals and (2) ceramics. There does not appear to be any intermetallics that have melting points high enough to compete with these two classes.

The refractory metals are Cr, Nb, Mo, Ta, W and Re. Electroplated chromium has worked well in the past, but it has some undesirable features. Its melting point is not very high, and as an electroplate it is too thin to insulate the underlying steel. Because it is thin, it does not damp out the thermal pulse, so that the underlying steel transforms. This promotes chromium cracking; cracking leads to coating failure. If it is plated thicker, the tensile residual stresses in the plate (inherent in the process) and low adhesive strength cause the coating to spall off. Unalloyed Nb is too soft, and its alloys have not been explored as a coating material. The advantages are that its modulus is similar to steel, and it is not as expensive as other refractory metals. Molybdenum tends to be easily embrittled by hydrogen. Alloys of Mo-Re show better ductility, but are expensive. Tantalum has been shown to work well unalloyed, and even better alloyed. However, it is the second-most expensive refractory metal. Tungsten and its alloys are very difficult to process, and easily embrittled by hydrogen. Rhenium is the most expensive refractory metal by far. It has been shown to promote ductility when used as an alloying agent in the other refractory metals.

It is instructive to examine the impact of coating material cost on the cost of gun tubes. For example, to coat a 120 mm M256 tank gun with 0.5 mm of material for its entire length is a volume of about 500 cm^3 of coating material. Using the 2001-2002 Alfa catalog [12], the price of each candidate material was used to roughly calculate the material cost of the coating. The least expensive forms of the pure elements were chosen for this exercise.

TABLE 1. Coating Materials Cost Calculations

Element	Form	Cost $/gm*	Density g/cm^3	Mass Req'd (g)	Coating Cost ($)
Cr	Broken plate	0.69	7.1	3550	2450
Nb	0.75 in rod	0.24	8.6	4300	1030
Mo	0.5 in rod	0.36	10.2	5100	1840
Ta	0.5 in rod	1.58	16.6	8300	13100
W	0.5 in rod	0.48	21.0	10500	5040
Re	0.2 in rod	25.8	19.3	9650	249000

*reference: 2001-2002 Alfa catalog [12]

These calculations will change if an alloy is used, if the material cost of the precursor form used is different, if the thickness of the coating is different, if the gun tube is partially coated, or if there is any amount of coating removed during final machining. It is readily apparent that rhenium is a non-starter solely based on cost, although it may be used as an alloying element. It is also readily apparent that there is a significant cost savings if a niobium alloy can be used.

The oxide, carbide and nitride ceramics can have extremely high melting points with excellent chemical resistance. Because of this, there have been a few attempts to use ceramics as coatings. Their downfall in the past has been poor adhesion, poor thermal and mechanical shock resistance [13].

There are many, many coating processes. Most of them can be removed from further consideration based on the manufacturing constraints above. As stated above, electroplated chromium has been perfectly adequate in the past. Unfortunately, the other refractory metals cannot be plated from aqueous solution. They can be deposited from fused salts, but this anneals the steel substrate [14, 15]. Thermal spraying of various types is feasible, but they either anneal the substrate or do not possess enough adhesion/cohesion in the service environment [16]. High rate magnetron sputtering shows promise [17]. Ion beam assisted deposition is too slow to build up the required thickness [18]. CVD produces a very uniform adherant coating, but currently operates at a temperature that anneals the substrate [19]. Laser cladding exhibits excessive mixing of the coating material with the substrate [20]. And so on. The coating process that best meets the above requirements is explosive bonding. A thick coating can be deposited with perfect adhesion very rapidly with negligible heating of the substrate. The refractory metal can be an alloy, but it must possess "enough" ductility. It is not difficult to integrate into the manufacturing sequence.

Under an ARO-ARL Phase II SBIR, TPL, Inc. explosively bonded tantalum on three 25 mm M242 Bushmaster barrels. Two of these barrels were test-fired at Aberdeen Test Center the week of 26 March 2001 with funds provided by the Naval Surface Warfare Center. The ammunition used was from the initial lot of M919 APFSDS-T, without the ablative paste. This lot was not fielded. It uses superhot HES9053 propellant that has an adiabatic

flame temperature of about 3700 K. This cartridge resembles a scaled-down high-performance tank gun cartridge. Standard Bushmaster barrels last 200-300 rounds with this ammunition. A no-twist rifled barrel and a smoothbore were tested, using the same firing schedule as was used with standard barrels. The rifled barrel was still serviceable after 600 rounds. The remaining 1385 rounds were fired through the smoothbore, and it continued to show good dispersion. Inspection of this barrel following testing showed that it only just started to breach the tantalum cladding. This barrel demonstrated a life in excess of five times the life of a standard barrel.

LINER

As opposed to the coating, the liner must be a stressed part of the gun tube. This may be part of a monobloc gun tube, or part of a built-up gun tube. The liner must have a high specific strength and a high fracture toughness. It should be under a residual compressive stress to maximize the mechanical efficiency of the gun tube. The amount of residual stress necessary depends on the liner's mechanical properties. It should have some amount of heat resistance (high melting point, retains modulus and strength). A low thermal conductivity and high thermal shock resistance are also advantageous.

Liners generally have been steels (16-inch Naval gun) or Stellite (.50 cal M2 machine gun). There have been numerous programs to use ceramics as liner materials. These have failed in the past because of the quality of the ceramic, and the inadequate axial preload in the guns tested. Another problem is the liner "walking" out of the jacket, or moving around inside the jacket as the gun is fired and thermally cycled. Also, heat-shrinking does not generate compressive residual stresses comparable to autofrettage. Coextrusion, as well as gas pressure bonding of a liner with a jacket have been tried [21], but these become difficult (expensive) in large caliber applications.

Built-up gun tubes are inherently expensive, especially as one goes up in size. Two-piece (liner-jacket) tubes that are accurately machined and heat-shrink-fit together are the most difficult to manufacture. These can be less expensive if the liner is made up of short sections. The cost of a built-up gun tube can be significantly reduced and the liner-jacket interface can be improved if a jacket can be wrapped around a liner.

JACKET

The jacket may also be part of a monobloc or built-up gun tube. Its materials requirements are similar to those of the liner: a very high specific strength and high fracture toughness. As a consequence of mechanical equilibrium, it will be under a residual tensile stress. It should also have a reasonable melting point and a high thermal diffusivity to dissipate waste heat faster.

Jacket materials have generally been high strength steels; they are predictable materials, and designers feel comfortable with them. They are inexpensive. The next best pressure vessel material is filament-wound graphite-epoxy composite. The polymer-matrix composites would be excellent low-weight alternatives to steel, except they do not possess the melting/decomposition point necessary in combination with their low thermal diffusivity. If the liner has sufficiently low thermal diffusivity, more heat is kept in the propellant gasses and less is put into the tube. There are some ceramics that possess a low thermal diffusivity

with good mechanical properties. ARDEC has an SBIR program that is exploring the combination of a ceramic liner that is put under the required preload by a polymer-matrix composite jacket.

Metal-matrix composite jackets [22, 23] have been tried with some success, but their inherent expense, coupled with their difficulty in manufacture has put them out of reach in the past. This may be changing with the inexpensive Nextel 610 fiber by 3M, and a program at ARL is examining this prospect.

"PAPER" GUN TUBES

Based on the above analysis, we are now in a position to design gun tube materials on paper. We will examine a tank gun tube, an artillery gun tube, an aircraft machine gun tube, and a mortar tube.

Tank Gun Tube

The tank gun barrel envisioned is similar to the existing 120 mm M256. It is a smoothbore, firing AP and HE projectiles with polymeric obturator bands. The "paper gun" has an autofrettaged monobloc high strength steel liner/jacket similar to the M256. However, it makes use of increased lethality propellant, which has a high adiabatic flame temperature, and so is quite erosive to steel. Electroplated chromium provides inadequate protection, since the substrate steel melts under the propellant's high flame temperature. Instead, a thick refractory metal is explosively-bonded to the steel substrate. How this would be produced is shown in Figure 2. The explosive bonding process must occur after the barrel forging has been heat-treated, autofrettaged, and the bore rough machined. The wall thickness must be fairly thick during explosive bonding, or else there will be plastic deformation of the tube. If a full-length clad is required, this difficulty can be obviated by the use of a suitable momentum trap around the thinner parts of the barrel.

Artillery Gun Tube

The "paper" artillery barrel is an artificially-cooled smoothbore, firing folding-fin high capacity projectiles with polymeric obturator bands. It is also an autofrettaged monobloc high strength steel liner/jacket with an explosively-bonded coating. The manufacturing sequence is similar to that for the paper tank gun tube in Figure 2.

However, if it must fire the existing inventory of 155 mm projectiles, it must be rifled. While the explosively-bonded coating can be made as thick as the depth of rifling, it must also be able to transmit the rifling torque to the projectile. It is unknown at this time whether a sufficiently strong refractory metal can be successfully bonded. The alternative is to initially produce a rounded rifling profile (similar to what is currently done for chromium electroplated rifled tubes). The refractory metal is bonded over that, and the tube is finish rifled. The difficulty of following the original rifling with the finish rifling tooling is acknowledged. The manufacturing sequence is shown in Figure 3.

Aircraft Machine Gun Tube

Although this application is not large caliber, it makes sense to present some ideas here. Ordinarily, a barrel that is lighter than a steel barrel is not really desirable due to stability issues. However, aircraft design places a high value on weight, and aircraft are inherently unstable firing platforms anyway. These guns are typically rifled with a progressive twist, and fire projectiles with polymeric or metallic rotating bands. For this application, the "paper" gun tube has no coating. It has a zirconia or silicon nitride ceramic liner with a graphite-epoxy composite jacket. The jacket is wrapped in tension over the liner, putting the necessary pre-stress (hoop and axial) on the liner. An ARDEC SBIR and a proposed ARL program are currently addressing this kind of a gun tube. The manufacturing sequence is shown in Figure 4.

Mortar Tube

Mortar and recoilless rifle barrels should also be lightweight. Titanium alloys have been tried for each [24, 25], but they suffer from extremely rapid erosion. An explosively-bonded refractory metal coating would prevent this. However, because it is a fairly thin-walled tube, the proper momentum trap must be devised to prevent the tube from plastically deforming during bonding. The tube gets quite hot in service during maximum firing rate, so the titanium must be a high temperature alloy, such as TIMETAL® 1100 or TIMETAL® 21S. The manufacturing sequence is shown in Figure 5.

An ARL program is currently examining the feasibility of using metal-matrix composites as a jacket material for mortars. These could be pressure cast around a steel liner. However, the required fatigue, thermal fatigue and high temperature fatigue must be demonstrated.

SUMMARY

There have been countless gun tube materials design experiments over the past century. Our level of understanding of the materials property requirements and materials processing, and the materials science and systems design that ties the two together allows us now to design gun tube materials systems that optimize value and cost. Using these principles, four gun tube materials systems (a tank gun, an artillery piece, an aircraft machine gun, and a mortar) were designed.

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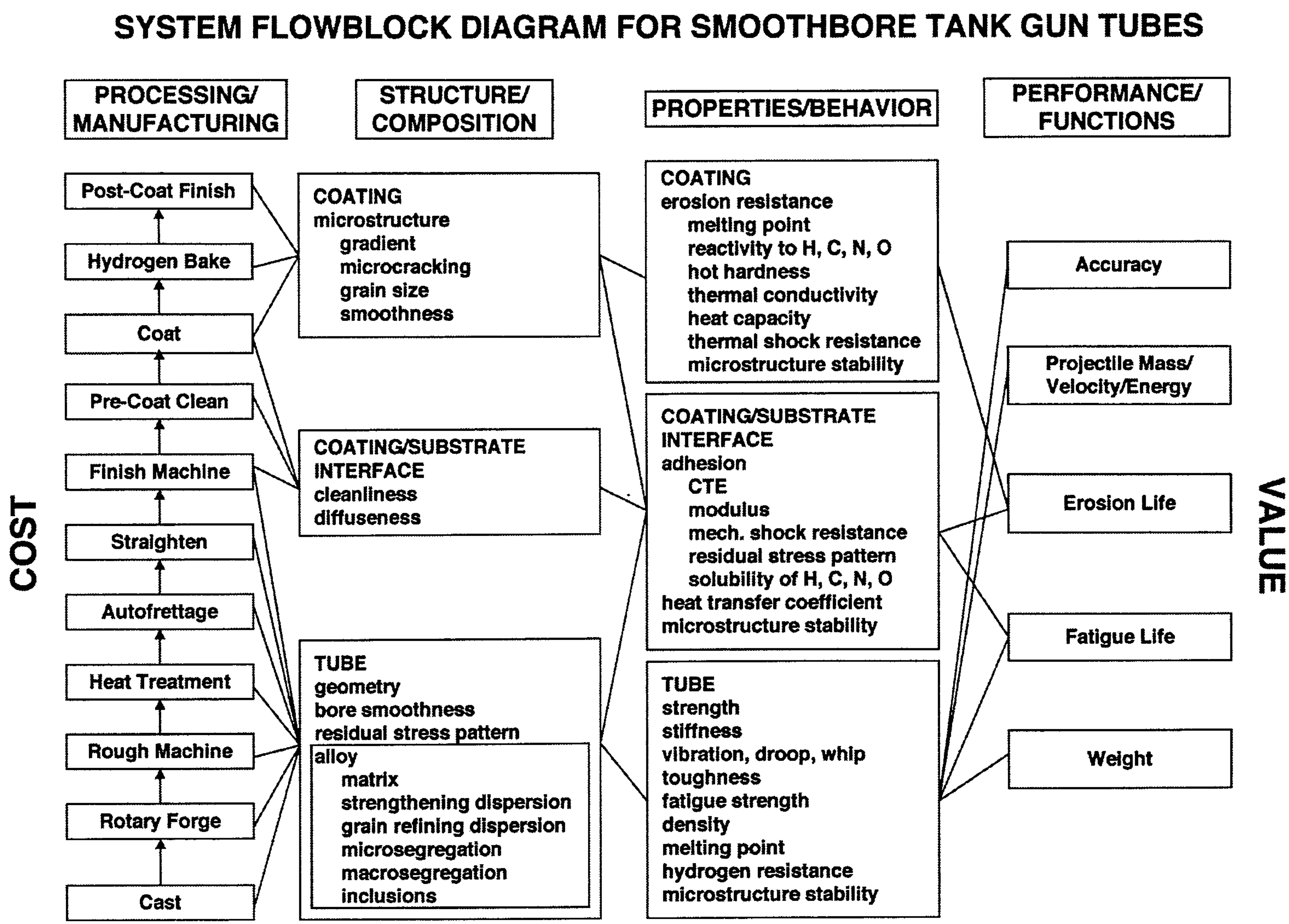

Figure 1. Tank Gun Tube Flow-Block Diagram

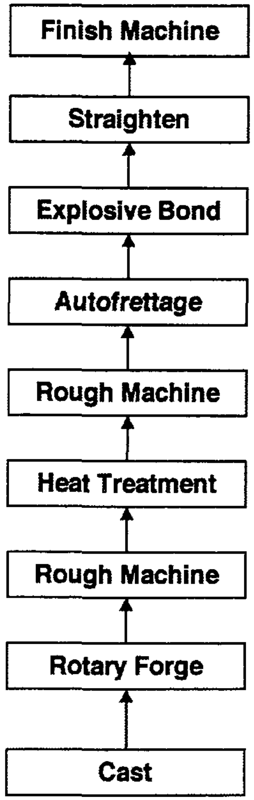

Figure 2. Manufacturing Sequence for a"Paper" Tank Gun Tube

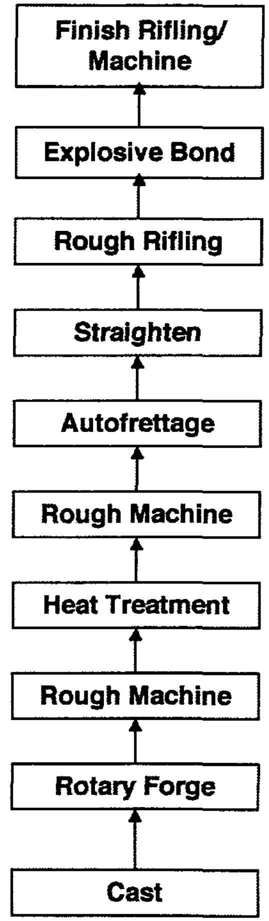

Figure 3. Manufacturing Sequence for a"Paper" Artillery Gun Tube

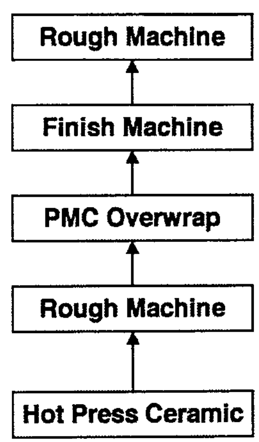

Figure 4. Manufacturing Sequence for a"Paper" Aircraft Machine Gun Tube

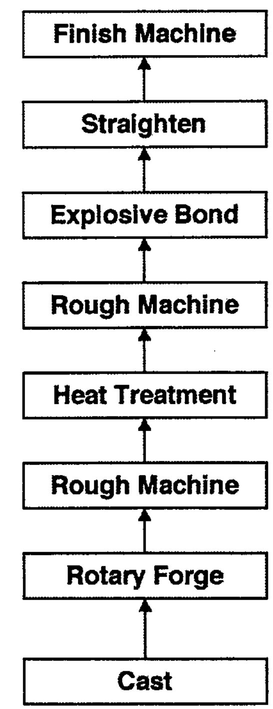

Figure 5. Manufacturing Sequence for a"Paper" Mortar Tube